

A solar dish concentrator based on ellipsoidal polyester membrane facets

G. Zanganeh^a, R. Bader^a, A. Pedretti^b, M. Pedretti^b, A. Steinfeld^{a,c,*}

^a Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland

^b Airlight Energy Holding SA, 6710 Biasca, Switzerland

^c Solar Technology Laboratory, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

Received 13 December 2010; received in revised form 29 August 2011; accepted 2 September 2011

Available online 3 October 2011

Communicated by: Associate Editor Robert Pitz-Paal

Abstract

The design of a solar parabolic dish concentrator is proposed based on an array of polyester mirror membrane facets that are clamped along their edges by elliptical rims and focused by applying a slight vacuum underneath the membranes, creating an ellipsoidal shape. The axes ratio of the elliptical rims varies with the position on the dish to approach the paraboloidal shape. The elastic mirror membrane deformation under uniform pressure load is simulated by finite element structural analysis and the resulting radiative flux distribution at the focal plane of the dish is determined by the Monte Carlo ray-tracing technique. Optimization of the membrane deflection is accomplished for maximum solar flux concentration at the focal plane. Two dish geometries are examined: (i) a 1.5-m radius 3-m focal length small dish, comprising 19 facets of 0.275-m radius with four different curvatures, yielding a peak solar concentration ratio of 5515 suns and a mean solar concentration ratio of 1435 suns with an intercept factor of 90% over a 3-cm radius disk target and (ii) a 10.9-m radius 11-m focal length large dish, comprising 121 facets of 0.9-m radius with 15 different curvatures, yielding a peak solar concentration ratio of 23,546 suns and mean solar concentration ratio of 8199 suns with an intercept factor of 90% over a 10.4-cm radius disk target. The performance of the second geometry is compared to that of the more conventional design of a multi-facet dish concentrator consisting of identical circular facets and shown to reach – on the same target area – a 12% higher mean solar concentration ratio as well as a 6.6% higher intercept factor. The simulated membrane shape is experimentally verified with photogrammetrical measurements carried out on a prototype facet of the small dish.

© 2011 Elsevier Ltd. All rights reserved.

Keywords: Solar energy; Parabolic dish concentrator; Pneumatic polymer facet; Monte Carlo; Finite element; Photogrammetry

1. Introduction

Besides modularity, solar parabolic dish concentrators offer high solar concentration ratios and hence high operating temperatures, leading to high solar-to-electricity efficiencies (DeMeo, 1997; Mancini et al., 2003; Schlaich, 1999; Stine, 1993). In order to reduce material demands, stretched-membrane dishes have been developed, typically

consisting of a thin (~ 0.1 mm) stainless steel support membrane that is spanned over a circular steel ring in a drum-like arrangement. Back-surface coated thin-glass mirror segments (Benina et al., 1995; Schiel et al., 1994) or metallized polymer membrane mirrors (Benina et al., 1995; Solar Kinetics, 1991) are attached to the steel support membrane. An exception is the 7.5 kW dish developed by Cummins Power Generation, Inc., which uses freely spanned thin polymer membranes (Bean and Diver, 1995), omitting the steel support membrane. Single-facet dish designs have f -numbers $f_{\text{dish}}/D_{\text{dish}} < 1$ and feature membranes that are deformed plastically by means of both uniform and

* Corresponding author at: Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland.

E-mail address: aldo.steinfeld@ethz.ch (A. Steinfeld).

Nomenclature

$A_{\text{dish,mirror}}$	projected dish mirror area (m ²)
C	solar concentration ratio
C_{mean}	area-weighted mean solar concentration ratio
$C_{\text{mean,ideal}}$	area-weighted mean solar concentration ratio over a flat disk target area, dimensioned to intercept all solar radiation reflected by an ideal paraboloidal concentrator
$C_{\text{peak,ideal}}$	peak solar concentration ratio at the focal plane of an ideal paraboloidal concentrator
D	diameter (m)
f	focal length (m)
f -number	ratio of focal length to diameter of dish or facet
E	Young's modulus (MPa)
G	shear modulus (MPa)
i	facet index
I_{sun}	direct normal solar irradiation (DNI) (kW/m ²)
I_{target}	local radiative flux on the target (kW/m ²)
P_{boundary}	point on facet boundary,
	$P_{\text{boundary}} = (x_{\text{boundary}}, y_{\text{boundary}}, z_{\text{boundary}})$ (m)
r	radial coordinate (m)
r_0	radial center point coordinate of facet boundary (m)
x, y, z	Cartesian coordinates

R_{facet}	radius of projected facet boundary (m)
W_{el}	electric power (kW)
R_{target}	radius of target (m)

Greek symbols

α	angle (°)
γ	intercept factor
$\eta_{\text{parasitics}}$	parasitic energy loss coefficient
η_{receiver}	receiver thermal efficiency
$\eta_{\text{solar-to-electricity}}$	solar-to-electric energy conversion efficiency
η_{Stirling}	efficiency of Stirling engine
ϕ_{rim}	rim angle of dish (°)
θ_{sun}	solar cone half-angle (0.267°) (°)
ϕ_0	azimuthal center point coordinate of facet boundary (m)
ρ	reflectivity
ν	Poisson ratio
ϕ	circumferential coordinate

Abbreviations

MC	Monte Carlo
FE	finite element

non-uniform loading to an approximate parabolic shape (Stine, 1993). In contrast, multi-facet dish designs have f -numbers of individual facets $f_{\text{facet}}/D_{\text{facet}} \cong 6$, allowing the membranes to be focused via elastic membrane deflection by applying uniform loading. In both cases, the deflected facet shape is maintained during operation by applying a slight vacuum underneath the membrane.

This paper deals with the optical design and analysis of a dish concentrator that is based on aluminized polyester mirror membranes which are spanned freely inside planar elliptical support rims, arranged on a paraboloidal surface, and focused by applying a small vacuum beneath each of the membranes. This yields approximate ellipsoidal mirror facet shapes that approach the ideal paraboloidal surface. Deformed facet shapes under uniform pressure loads are calculated by finite element (FE) analysis and resulting focal radiative flux distributions are determined by Monte Carlo (MC) ray-tracing. The optimum pressure loads to be applied to the facets are determined for maximum radiative flux concentration at the target plane. The performance of the proposed dish design with elliptical facet rims is compared to the more common design with circular rims. Numerical results are validated with photogrammetric shape measurements on a prototype facet.

2. Optical design

Two dish geometries are investigated: (a) a small dish with 1.5-m radius and 3-m focal length, comprised of 19

facets with four different facet curvatures, and (b) a large dish with 10.9-m radius and 11-m focal length, comprised of 121 facets with 15 different curvatures. The number of facets resulted from a trade-off between optical efficiency, dish surface coverage, and manufacturing costs. Facets are arranged on the projected dish area as shown in Fig. 1. The intersection of a paraboloid of revolution with parallel cylinders yields planar elliptical facet perimeters with constant minor axes aligned tangentially to the paraboloid's circumference, and with major axes oriented radially and increasing in length with the radial position of the facet. The boundary of facet i is described in 3D by:

$$P_{\text{boundary},i} = \begin{pmatrix} x_{\text{boundary},i} \\ y_{\text{boundary},i} \\ z_{\text{boundary},i} \end{pmatrix} = \begin{pmatrix} r_{0,i} \cos \varphi_{0,i} + R_{\text{facet}} \cos \alpha \\ r_{0,i} \sin \varphi_{0,i} + R_{\text{facet}} \sin \alpha \\ \left(x_{\text{boundary},i}^2 + y_{\text{boundary},i}^2 \right) / 4f \end{pmatrix}, \quad 0 \leq \alpha \leq 2\pi \quad (1)$$

where $r_{0,i}$ and $\varphi_{0,i}$ are radial and azimuthal center point coordinates of the boundary of facet i (Fig. 1) and R_{facet} is the radius of the projected facet area: $R_{\text{facet}} = 0.275$ m for the small dish and $R_{\text{facet}} = 0.9$ m for the large dish. As an example, the facet geometries of the small dish are given in Table 1. While the ratio of semi-major to semi-minor axes is close to unity for all facets of the small dish, it

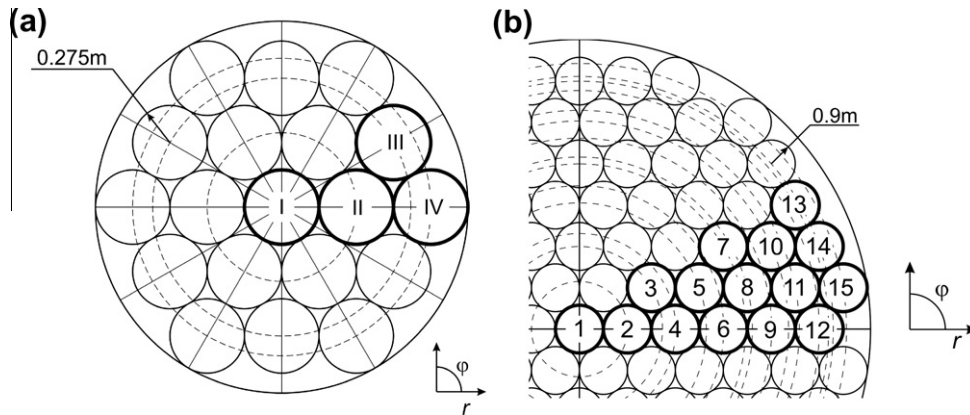


Fig. 1. Facets arrangement: (a) small dish with 1.5-m radius and 3-m focal length (28°-rim angle), comprising 19 facets with four different facet curvatures; (b) large dish with 10.9-m radius and 11-m focal length (53°-rim angle), comprising 121 facets with 15 different curvatures.

Table 1

Facet types and number of facets of each type contained by the dish, center point coordinates of facet perimeters r_0 , ϕ_0 , length and slope of semi-major axes of elliptical facet perimeter for the small dish design (Fig. 1a).

Facet type	No. of facets	Radial coordinate of facet center point r_0 (m)	Azimuthal coordinate of facet center point ϕ_0 , (°)	Length of semi-major axis (m)	Slope of major axis (°)
I	1	0	0	0.275	0
II	6	0.6	0,60,120,180,240,300	0.276	5.71
III	6	1.04	30,90,150,210,270,330	0.279	9.82
IV	6	1.2	0,60,120,180,240,300	0.280	11.31

reaches up to 1.1 in case of the large dish due to its increased rim angle.

The solar concentration ratio, C , is defined as the radiative flux at the focus, normalized to the direct normal solar irradiation I_{sun} . For an ideal paraboloidal concentrator (no mirror imperfections or tracking errors, perfectly specular) of rim angle ϕ_{rim} , C is maximum and uniform within the paraxial image of the sun at the focal plane: the so-called “hot spot” (Bliss, 1957):

$$C_{\text{peak,ideal}} = 4 \sin^2(\phi_{\text{rim}}) / (2\theta_{\text{sun}})^2 \quad (2)$$

where $\theta_{\text{sun}} = 4.66$ mrad. The area-weighted mean solar concentration ratio on a circular disk target is defined as:

$$C_{\text{mean}} = \frac{1}{I_{\text{sun}}} \frac{1}{\pi R_{\text{target}}^2} \cdot 2\pi \int_0^{R_{\text{target}}} I_{\text{target}}(r) \cdot r \cdot dr \quad (3)$$

where I_{target} is the local radiative flux on the target and R_{target} is the target radius. For an ideal paraboloidal concentrator with a target dimensioned to intercept all radiation reflected by the concentrator:

$$C_{\text{mean,ideal}} = \frac{\sin^2(\phi_{\text{rim}}) \cos^2(\phi_{\text{rim}} + \theta_{\text{sun}})}{\sin^2(\theta_{\text{sun}})} \quad (4)$$

$C_{\text{mean,ideal}}$ is maximized for $\phi_{\text{rim}} \approx 45^\circ$. (Rabl, 1976) Small rim angles result in a less curved dish surface, which can be well approximated by membranes stretched on circular or elliptical facets subjected to differential pressure (Fichter, 1997). In the present case, $\phi_{\text{rim}} = 28^\circ$ is chosen for the small dish to facilitate approximation of the paraboloid with a small number of facets, while $\phi_{\text{rim}} = 53^\circ$ is chosen

for the large dish containing a larger number of facets in order to reach higher concentrations.

Nonlinear structural deformation analyses of the membranes were conducted by applying 10^5 and 10^6 incremental load steps for small and large dish, respectively, with up to 200 iterations in each step (ANSYS® 12.0). The material was modeled orthotropic with Young's modulus and Poisson's ratio given by the membrane manufacturer in machine and transversal direction. Since the material has near-isotropic properties, the shear moduli were calculated with the relation for isotropic materials, $G = 0.5E/(1 + \nu)$ (Brockenbrough and Merritt, 1994). Tri-mesh elements (SHELL 281) were used to facilitate calculation of surface normal vectors on the deformed elements for subsequent ray-tracing analyses. A grid convergence analysis performed to minimize the discretization error indicated that an element edge length of 1 and 3 cm for the small and large dish facets, respectively, yields approximately 6500 elements per facet and delivers an optical performance approaching that of the non-discretized shape for an ideal facet. Fixed translational and free rotational degrees of freedom were applied at the membrane boundaries, due to negligible stiffness of the membranes (thickness: 50 μm). Uniform pressure loads were applied to the membranes and optimized for maximum C_{mean} on the target area by iterating between FE and MC ray-tracing analyses.

MC is applied for each facet type to determine the distribution of C at the focal plane as well as C_{mean} as functions of radius r of the disk target positioned at the focal

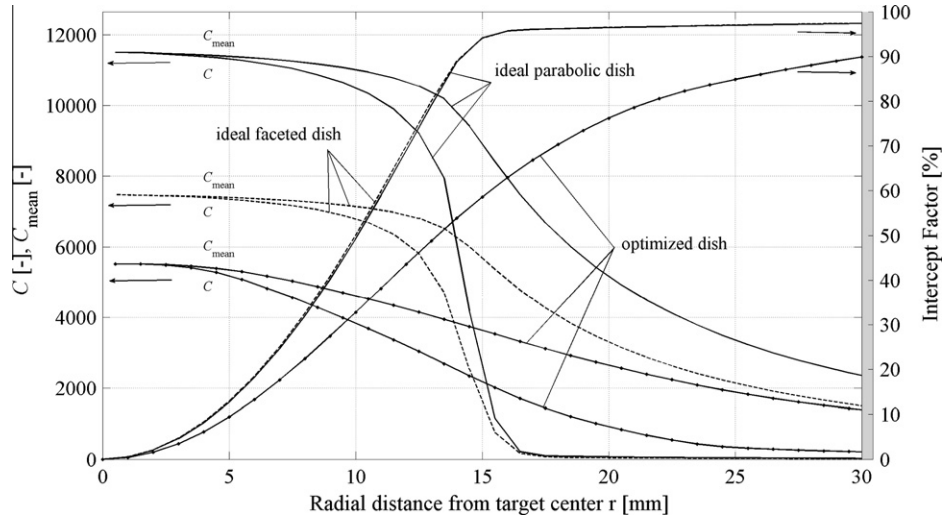


Fig. 2. Solar concentration ratio C , mean solar concentration ratio C_{mean} , and intercept factor γ , as functions of the radial distance r from the target center, for the optimized small dish, an ideal paraboloidal concentrator, and an ideal faceted paraboloidal concentrator.

plane (Siegel and Howell, 2002). Also computed is the intercept factor γ , defined as the percentage of solar radiation incident on the target plane that is captured by the target, as a function of radius r . As r increases, γ approaches 100%. Numerical description of the deformed membranes is given by the node triples spanning each mesh element. Surface normal vectors are derived from the node positions. Incident rays are distributed over the surface elements in proportion to the projected element areas, and specularly reflected (with $\rho = 1$) from the element's center of gravity. The sunshape model (Buie, 2003) with circumsolar ratio of 5% is used to determine the rays incidence direction on the dish. For simplicity, shading by the target, mirror specularity errors, tracking errors, and receiver misalignment are omitted from consideration; these are obviously important for the overall system performance, but their exclusion do not affect the main conclusions of this analysis. Contributions of all facets are summed up to determine the total focal radiative flux distribution for the entire dish. 10^7 sunrays are used in each MC run, resulting in a statistical error below 0.1%.

3. Results

Fig. 2 shows the C -distribution, $C_{\text{mean}}(r)$, and $\gamma(r)$ for the optimized small dish. Also shown are the results obtained for an ideal paraboloidal concentrator and for a faceted concentrator with facets that coincide exactly with the paraboloid of revolution and have cross-sectional areas equal to those of the proposed design. The small dish reaches $C_{\text{mean}} = 1435$ suns and $\gamma = 90\%$ on a 3-cm radius target. The corresponding values are 2605 suns and 97.4% for the ideal parabolic dish, and 1663 suns and 97.4% for the ideal faceted paraboloidal concentrator. Note that 63.9% of the projected small dish area is covered

with mirrors, hence 36.1% of the solar radiation incident on the dish is lost through spaces between the facets. The radiative flux distribution has a typical Gaussian shape due to optical imperfections. Solar cavity-receivers can be designed to homogenize the flux on the absorber after multiple internal reflections. Secondary concentrators (e.g. CPC) or optical mixers could be implemented for applications requiring a pill-box distribution (e.g. concentrated photovoltaics).

Optimum differential pressures to be applied to the non-prestressed facets of the small dish are 42, 41, 39, and 38 Pa for facet types I, II, III, and IV, respectively (see Fig. 1). Optimum membrane deflections and hence optimum differential pressures decrease with radial position of the facets, in accordance with the decreasing curvature of an ideal paraboloid. The resulting maximum stresses occurring in the membranes are judged against the membrane's tensile strength and resistance to creep and found to be acceptably low.

The results for the large dish are shown in Fig. 3. On a 10.4-cm radius target, $C_{\text{mean}} = 8199$ suns and $\gamma = 90\%$. Corresponding values are 10,679 suns and 97% for the ideal paraboloidal concentrator, and 8778 suns and 97% for the ideal faceted paraboloidal concentrator. 82.2% of the projected large dish area is covered with mirrors, hence 17.8% of the solar radiation incident on the large dish is lost between the facets. For the same γ , the large dish reaches more than five times higher C_{mean} than the small dish. This is due to its larger rim angle and the increased number of facets used, leading to a better covering of the projected dish area with mirrors and better approximation of the paraboloidal shape with facets.

For the large dish, the proposed design with different elliptical facets is compared to the more conventional design with identical circular facets. The dimension of all of the facets for the latter case is identical to the facet type placed

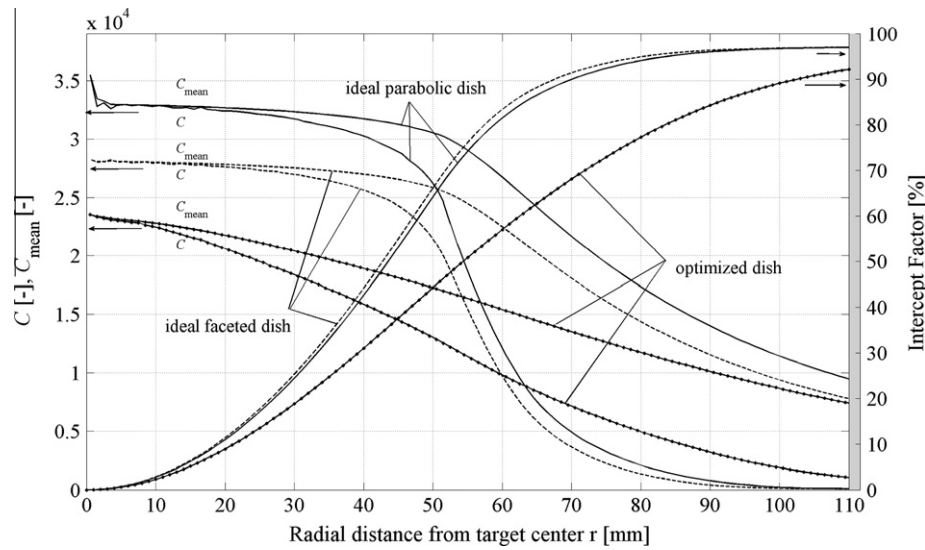


Fig. 3. Solar concentration ratio C , mean solar concentration ratio C_{mean} , and intercept factor γ as functions of radial distance r from the target center, for the optimized large dish, an ideal paraboloidal concentrator, and an ideal faceted paraboloidal concentrator.

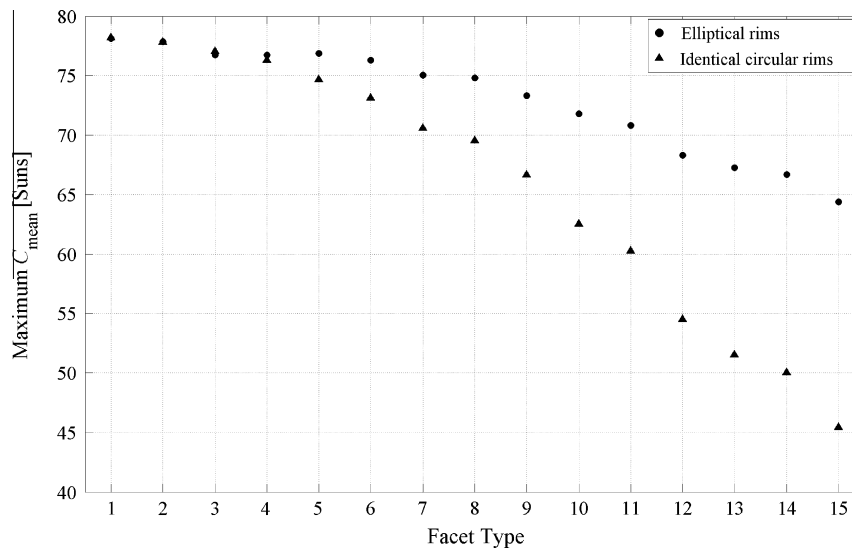


Fig. 4. Maximum achievable mean solar concentration C_{mean} on a 10-cm radius target on the focal plane as a function of facet position on the dish, for the proposed design with varying elliptical facets (●) and for the more common design with identical circular facets (▲).

in the center of the paraboloid, denoted by 1 in Fig. 1b. The projected area of all of the facets of the proposed design is a circle. In contrast, the projected area of the circular rims is – with exception of the center facet – an ellipse, resulting in an overall 5% worse coverage of the paraboloid surface with respect to the proposed design. For both cases, the mean solar concentration ratio of every facet type (depending on its position on the dish) is optimized for a 10-cm radius circular target area on the focal plane. The results are plotted in Fig. 4. For both cases, the mean concentration decreases with increasing radial position due to off-axis aberrations. However, the increasing difference in the achievable mean concentration between the two cases with increasing distance from the paraboloid center shows that

elliptical rims approximate the parabolic shape better than circular rims. For the facets close to the center of the dish the mean concentrations are comparable for both cases. However, for facet type #15, placed the farthest away from the paraboloid center, the difference is 42%. Its projected area is 9% larger for the elliptical case. The dents in the curve, especially noticeable at the points corresponding to facet types 7, 12, and 14, are due to the varying radii of the concentric circles on which the centers of the facets are placed, as indicated in Fig. 1b.

The local and mean concentration profile as well as the intercept factor on the focal plane for the two cases is shown in Fig. 5. During the optimization process, each facet type is optimized for maximum C_{mean} on a 10 cm

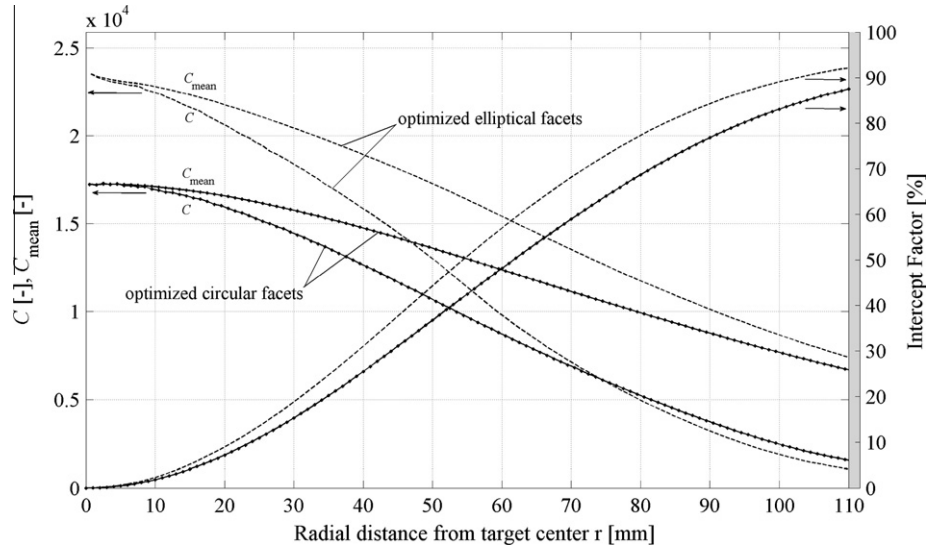


Fig. 5. Solar concentration ratio C , mean solar concentration ratio C_{mean} , and intercept factor γ as functions of radial distance r from the target center, for the optimized large dish with elliptical facet rims and with identical circular facet rims.

Table 2

Parameters used to estimate electric power output of dish/Stirling engine system; receiver efficiency, Stirling engine efficiency, and parasitic loss coefficient are estimates based on the data given by Stine (1993) and Noyes (1990) for the 50 kW dish/Stirling system.

mirror reflectivity ρ	0.92
projected dish area covered with mirrors $A_{\text{dish,mirror}}$ (m ²)	307.9
Solar flux I_{sun} (kW/m ²)	0.9
intercept factor γ	0.9
receiver efficiency η_{receiver} (Stine, 1993)	0.8
Stirling engine efficiency η_{Stirling} (Stine, 1993)	0.42
parasitic loss coefficient $\eta_{\text{parasitics}}$ (Noyes, 1990)	0.9

radius target. The overall dish is designed for $\gamma = 90\%$, which corresponds to a 10.4 cm radius target. With elliptical facets and hence better approximation of the ideal paraboloidal surface, the intercept factor γ and the mean concentration C_{mean} on a 10.4-cm radius target are 6.6% and 12% higher, respectively. The peak concentration is 37% higher for the case with elliptical rims.

If the solar concentrator is coupled with a Stirling engine, the electric power output is calculated from:

$$\dot{W}_{\text{el}} = \rho A_{\text{dish,mirror}} I_{\text{sun}} \gamma \eta_{\text{receiver}} \eta_{\text{Stirling}} \eta_{\text{parasitics}} \quad (5)$$

With the parameters listed in Table 2, an electric power output of $\dot{W}_{\text{el}} = 69.4$ kW can be achieved, corresponding to a solar-to-electrical energy conversion efficiency of $\eta_{\text{solar-to-electricity}} = 25\%$.

4. Experimental validation

In order to verify the simulated deformed membrane shapes, a prototype facet of type IV of the small dish, as indicated in Fig. 1a, was fabricated using 50 μm -thick Mylar[®] polyester mirror membrane. The experimental setup is shown in Fig. 6a. The mirror membrane is pre-stressed

and clamped between two identical elliptical rings with dimensions given in Table 1. A gas tight enclosure below the membrane is created by attaching a steel plate to the lower ring. The enclosure is evacuated with a fan to create a uniform pressure load on the membrane. Pressure is measured with a pressure transmitter by SensorTechnics (range 0–70 mbar, accuracy ± 0.05 mbar). 3D coordinates of 188 points on the membrane surface are measured by photogrammetry (Eos Systems Inc., PhotoModeler 6) using a Nikon D80 camera (resolution 3872×2592 , focal length 18 mm, precision 1:30'000) (Shortis and Johnston, 1996). The average absolute error of the photogrammetric measurements is 0.02 mm. The surface is modeled with a 3D surface fit (gridfit.m, John D'Errico © 2006) based on the measured surface points for use in the ray-tracing simulation. To remove corrugations in the membrane, the membrane is pre-stressed prior to the experiments by exposing the facet assembly to 250 °C hot air in an oven for 30 s. Fig. 6b shows the simulated C_{mean} on a 3-cm radius disk target as a function of the applied pressure load obtained with the experimentally determined facet shape. Optimum membrane deformation is reached at a differential pressure of 139 Pa (vs. 38 Pa for the non-prestressed membrane), yielding $C_{\text{mean}} = 80$. With the optimum simulated shape obtained with FE analysis, the corresponding C_{mean} is 80 as well.

Fig. 7 shows the C -distribution and intercept factor γ as a function of target radius r for facet type IV of the small dish. Shown are the curves for the measured and simulated optimum shapes, and the curve for the ideal paraboloidal shape. The slope error field for the two cases with respect to the ideal paraboloidal shape is illustrated in Fig. 8. For both cases, the slope errors are largest on the edge of the facet, decrease to a minimum, rise again slightly, and reach the lowest value in the facet center. The root mean square of the slope angle deviations is 2.2 mrad between

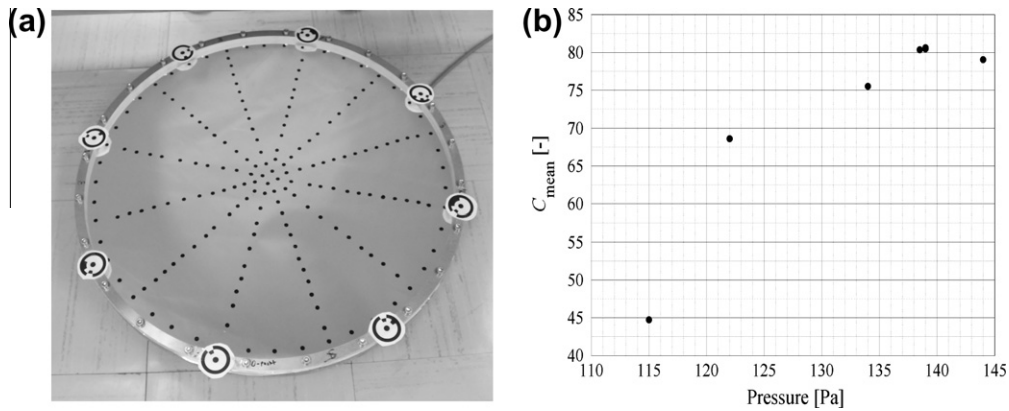


Fig. 6. (a) Experimental setup to measure the deflected facet shape under uniform pressure load using photogrammetry; (b) C_{mean} on a 3-cm radius disk target as a function of the applied pressure load obtained with the experimentally determined facet shape.

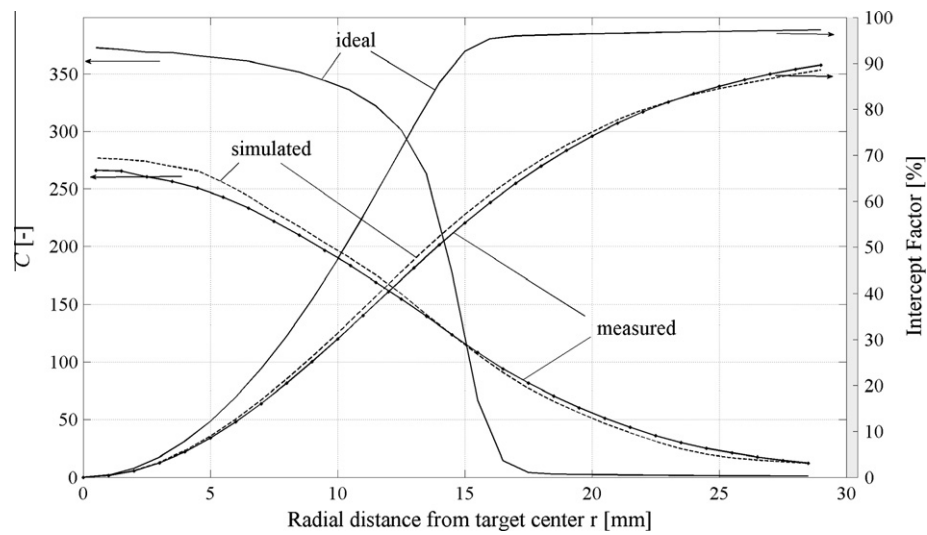


Fig. 7. Solar flux concentration C and intercept factor γ as functions of radial distance from the target center, for measured and simulated facet IV shapes, and for the corresponding ideal paraboloidal facet shape.

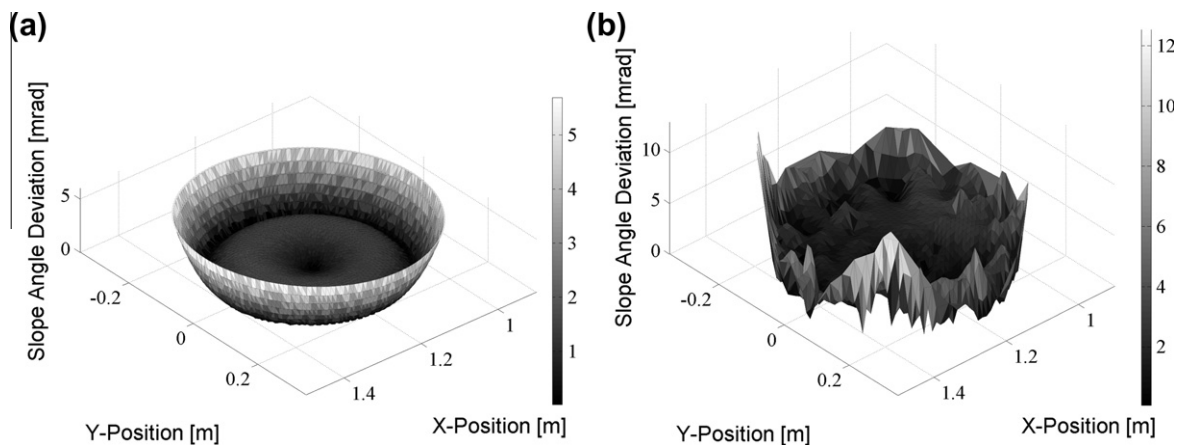


Fig. 8. Slope error field with respect to ideal paraboloidal surface for (a) with FE analysis simulated shape and (b) the photogrammetrically measured shape.

simulated and ideal paraboloidal shapes, and 2.8 mrad between photogrammetrically measured and ideal paraboloidal shapes. The close values for the two cases also agree well with the similar concentration profile obtained by the two shapes via Monte Carlo ray-tracing, as illustrated in Fig. 7.

Best agreement of the measured and simulated flux distributions was obtained when (microscopic) imperfections in mirror surface and specularity are omitted, indicating that both effects are negligible compared to those caused by macroscopic mirror shape imperfections, as observed in a previous study (Bader et al., 2009).

5. Conclusions and outlook

We analyzed the optics of a solar dish concentrator made of pneumatically deflected polyester membrane mirror facets mounted on elliptical frames. Membrane deflections were optimized for maximum solar concentration ratio using coupled FE structural and MC ray-tracing simulations. A small dish with 1.5-m radius and 28°-rim angle captures 90% of the incident solar radiation on a 3-cm radius target at an average solar concentration ratio of 1435 suns. Improved results are obtained with a 10.9-m radius dish with 53°-rim angle, capturing 90% of the incident solar radiation on a 10.4-cm radius target at an average solar concentration ratio of 8199 suns. Reference values obtained with ideal paraboloidal concentrators are 97.4% and 2605 suns for the small dish, and 97% and 10,679 suns for the large dish. Superior performance of the large dish vis-a-vis the small dish is due to its larger rim angle, better covering of the dish surface by the mirror facets, and closer approximation to the ideal paraboloidal shape using a larger number of (comparatively smaller) facets. Small differential pressures of a few mbar are sufficient to focus the facets, thus reducing the loads exerted on the support rim and air leakage into the evacuated space. Simulations were verified with photogrammetric measurements on a prototype facet. To protect the thin mirror membranes from wind, rain, and dust, the mirror setup can be enclosed by an inflated air bubble made from transparent ETFE-material, similar to a novel parabolic trough concentrator (Bader et al., 2009), which has proven satisfactory durability in outdoor applications and resistance to UV-light and abrasion. The performance of the proposed large dish design with elliptical facet rims is compared to the more common design with circular rims. On a 10.4-

cm radius target, the dish captures 6.6% more radiation and reaches 12% higher average concentration with elliptical facets vis-à-vis circular facets.

Acknowledgements

This study has been partially funded by the BfE – Swiss Federal Office of Energy.

References

- Bader, R., Haueter, P., Pedretti, A., Steinfeld, A., 2009. Optical design of a novel 2-stage solar trough concentrator based on pneumatic polymeric structures. *ASME Journal of Solar Energy Engineering* 131, 0310071–0310079.
- Bean, J.R., Diver, R.B., 1995. Technical Status of the Dish/Stirling Joint Venture Program.
- Beninga, K.J., Davenport, R.L., Johansson, S.N., 1995. Design, testing, and commercialization plans for the SAIC/STM 20 kW sub(e) solar dish/stirling system.
- Bliss, R.W., 1957. Notes on performance design of parabolic solar furnaces. *Solar Energy* 1, 22–29.
- Brockenbrough, R., Merritt, F., 1994. *Structural Steel Designer's Handbook*, 3 ed. McGraw-Hill.
- Buie, D., 2003. Sunshape distributions for terrestrial solar simulations. *Solar Energy* 74, 113–122.
- DeMeo, E.A., 1997. *Renewable Energy Technology Characterizations*, US Department of Energy, O.o.U. Technologies, TR-109496.
- Fichter, W.B., 1997. Some Solutions for the Large Deflections of Uniformly Loaded Circular Membranes, Langley Research Center, NASA Technical Paper 3658.
- Mancini, T., Heller, P., Butler, B., Osborn, B., Schiel, W., Goldberg, V., Buck, R., Diver, R., Andracka, C., Moreno, J., 2003. Dish-stirling systems: an overview of development and status. *Journal of Solar Energy Engineering* 125, 135.
- Noyes, G.W., 1990. The effect of component efficiency and operating conditions on the 50 kW dish stirling system in Riyadh, Saudi Arabia. *ASME Journal of Solar Energy Engineering* 112, 244–246.
- Rabl, A., 1976. Comparison of solar concentrators. *Solar Energy* 18, 93–111.
- Schiel, W., Schweitzer, A., Stine, W.B., 1994. Evaluation of the 9-kW(e) dish/Stirling system of Schlaich Bergermann und Partner using the proposed IEA dish/Stirling performance analysis guidelines.
- Schlaich, J., 1999. Tension structures for solar electricity generation. *Engineering Structures* 21, 658–668.
- Shortis, M.R., Johnston, G.H.G., 1996. Photogrammetry: an available surface characterization tool for solar concentrators, Part I: Measurements of surfaces. *Journal of Solar Energy Engineering* 118, 146–150.
- Siegel, R., Howell, J., 2002. *Thermal Radiation Heat Transfer*, 4 ed. Taylor&Francis, New York.
- Solar Kinetics, I., 1991. Development of a stretched-membrane dish.
- Stine, W.B., 1993. An international Survey of Parabolic Dish/Stirling Engine Electrical Power Generation Technology.